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REGULAR ARTICLE

Technique to Optimize the Optical Properties of Nanomaterials for Photonic Sensors

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Surface Plasmon Resonance (SPR) is a phenomenon in which electrons at the interface of dielectric and metal vibrate coherently in response to incoming plasmons. It is commonly employed in photonic sensors due to its sensitivity to material properties, making it useful in domains such as biosensing and biomedical applications. Various parameters, particularly the thickness of the metal layer, have a considerable impact on SPR performance, necessitating exact modifications to generate the best resonance signal. Existing research has failed to delve into in-depth analysis about how the thickness of gold layers influences SPR properties under controlled conditions. The research aims to explore the influence of different gold layer thicknesses on the SPR signal and to find the optimal thickness for getting the best resonance angle and reflectance characteristics. Thin gold films were created using an experimental process, with the thickness regulated by ion-beam sputtering–deposition. The SPR resonance was measured by altering the gold layer's depth and recording the resulting reflection spectrum. The resonance angle shifts were investigated utilizing the plasmonic Otto configuration at a given wavelength in an air-based dielectric medium. The research showed that changes in gold layer thickness caused considerable adjustments in the resonance angle. The results show that there is an optimal thickness range for maximum SPR performance, with minimal reflection and optimal resonance.

Keywords: Surface plasmon resonance (SPR), Gold layer, Otto configuration, Photonic sensors, Thickness, Ion-beam sputtering-deposition.

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1. INTRODUCTION

In the past several decades, scientists have intensively focused on new photodetector development because of rising optoelectronic and photonic application standards. The performance of most applications needs photonic sensors for their operation, including bio-photonic electronics accompanied by optical communications, remote-control appliances and wise imaging systems [1]. The stability combined with plasmonic properties makes Au (Gold) the most adopted metal material for various applications. Research within the literature focuses on a general optimization of gold layer thickness through inaccurate experimental procedures within controlled environments while causing variations in detection sensitivity and accuracy [2]. Such performance-based characteristics of nanomaterials affect sensor operations through their absorption mechanisms, reflectivity patterns, photoluminescence effects as well as through refractive index effects. 2D layered metal chalcogenides stand out among these materials because they offer high optical sensitivity and quick response time along with low dark current and excellent signal-to-noise ratio [3]. Such materials enable

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flexible, transparent, portable devices that can be integrated into wearable and portable bio-imaging systems. The benefits of nanomaterial usage in photonic sensors do not eliminate continuing difficulties that exist during their optimization process. Light absorption efficiency remains limited and structural stability is low while controlling optical properties for sensitive sensing operations remains uncontrolled [4]. Scientists have utilized three traditional procedures, namely chemical doping together with strain engineering and surface functionalization, to enhance the optical responses from nanomaterials. However, the aforementioned methods typically possess drawbacks in the form of material degradation, complex fabrication processes, and unknown performance across a variety of conditions [5].

In addition to this, optical sensing systems being miniaturized require compact light-transmitting devices. Multi-core fiber bundles, as part of optical fibers, have come forward as candidate solutions owing to their thin diameter (1-2 mm) and ability to transmit light with reduced loss. Fiber-optic couplers are widely used to couple these fibers with light sources and detectors, further enhancing sensor efficiency [6]. Recently, bio-inspired chiral nanomaterials have been studied for their possible use in photonic sensor applications. Chirality, or the phenomenon by which materials display non-superimposable mirror images, is a key aspect of increasing light-matter interactions to achieve increased selectivity and specificity in optical sensing and catalysis [7]. The processes that control chirality transfer from spanning atomic to bulk dimensions, however, are not well understood, and hence, it becomes difficult to design chiral inorganic nanomaterials with specified optical properties. Deriving lessons from biological chirality transfer processes can offer a route to designing next-generation nanomaterials with maximized optical properties for photonic sensors [8].

2. RELATED WORKS

The optical behavior of metal-based nanomaterials and applications in ultrafast photonics were investigated [9]. Metal nanoparticles optimized material properties optically by SPR and by bandgap nanostructures and quantum phenomena in metal oxide nanoparticles. The potential was applied in mode-locked and Q-switched lasers but led to major difficulty in managing synthesis, stability, and scalability. Interplay complications in transition metal oxides also limited complete optimization for photonic applications. Photonic crystals (PhCs) with photonic stop bands (PSBs) increase light-matter interactions, allowing for sophisticated optical sensing [10]. Bottom-up assembled PhCs provided high analyte adsorption and structure tunability for enhanced performance. Sensing mechanisms involved refractive index shifts, changes in lattice spacing, fluorescence, and Raman spectroscopy. Structural control, fabrication complexity, and environmental stability pose some challenges.

Optical colorimetric photonic crystal (PC) sensors improved sensitivity using material improvement, sensor fabrication, and multisensory integration [11]. Techniques such as molecular design, sensor-analytical interaction, and double-signal sensing enhanced mechano-sensors and chemo-/biosensors. These provided more accurate detection but struggled with deformability control and precision manufacturing. The research should aim to optimize optical properties and analytical procedures for real-world applications. The research intended to create SiC/TaC nanostructure-doped PC as an economical, light material with high optical properties for optoelectronics [12]. The nanostructures were prepared and the optical properties were measured, with an improvement in 25 % absorption and a reduction in energy gap from 3.69 eV to 3.2 eV at 4.8 wt% for SiC/TaC. The results produced enhanced optical absorption and were relevant to photonic applications. This method lacks optimization and assessment of long-term stability, which remain crucial for real-world applications.

3. METHODOLOGY

This section deliberated the working of photonic sensors with its configurations, and an analysis on the influence of different gold layer thicknesses on the SPR signal.

3.1 Working Principle of Photonic Sensors

The thickness of the metal layer is a crucial parameter in calculating the act of the SPR sensor. Gold is preferably used as the metal layer due to its superior chemical stability, low rate of oxidation, and resistance to surrounding contaminants, ensuring that it can be used over an extended period. Gold is also more sensitive at visible wavelengths than other metals with stable plasmonic resonance. SPR has garnered considerable attention due to its excellent efficiency in label-free detection techniques, which find broad applications in biosensing, photonics, and biomedical diagnostics. The sensitivity of an SPR system is strongly dependent on the depth optimization of the metal sheet since it has a direct impact on the quality conditions.

According to experimental observations, SPR appears at a certain resonance angle where the minimum reflection is measured, confirming the close relationship between film thickness and resonance efficiency. Typically, an Otto configuration encompasses a metal layer (gold) placed on a dielectric layer, with an additional dielectric medium (air) introduced at the other side of the metal layer. The reflectance and incident angle relationship is founded on the interface interaction at the metal dielectric, and the relationship relies on the dielectric response and optical refractivity of the surrounding material. The interaction is numerically simulated to determine optimal thickness ranges to achieve maximum SPR sensitivity. The least amount of light that is returned to the detector (not reflected) is shown in Fig. 1.

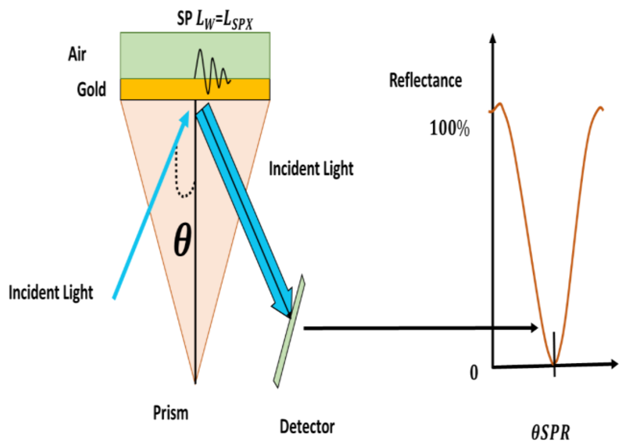

Fig. 1 – Minimum reflection occurred at θ_{spr}

3.2 System Configuration

The monochromatic laser beam employed in this research was set to a wavelength of 632.8 nm, and a 10 cm focal length lens was utilized to focus the incident light onto the gold-coated prism. Surface plasmon waves (SPW) were excited at the metal-dielectric interface in which the dielectric medium was air with a refractive index of 1. Thin films of gold were prepared using the ion-beam sputtering deposition technique with high control over the thickness of the layers. The deposition was performed in a vacuum chamber to avoid oxidation and contamination, with the starting gold layer thickness at 10 nm and further layers deposited stepwise up to thicknesses of 70 nm. Atomic force microscopy was employed to track the gold film thickness to ensure homogeneity and surface smoothness. Substrates were built of prism-shaped glass with a refraction index of 1.51 and size 1.5 cm × 1.5 cm. Reflectance spectra versus the incident angle were measured to find the resonance conditions for surface plasmon resonance using a photodetector to monitor the intensity of reflected light to locate the minimum reflectance point indicating the resonance angle. The resonance angle shifts were also investigated in terms of changes in gold layer thickness, validating the film thickness-resonance performance relationship. The coupling between light and the gold layer was studied with Attenuated Total Reflection, where the evanescent field at the interface enabled plasmon excitation. The energy of the incident light was transferred to electron oscillations in the gold film to form a plasmonic field. The reflectance and resonance angle measurements were thoroughly investigated to establish the optimal thickness range for sensitivity maximization, which has helped to create high-performance surface plasmon resonance-based sensors with improved detection accuracy for biosensing, photonics, and biomedical diagnostics applications.

SPR takes place at the connection between the second medium and the metal sheet. The surface plasmon wave vector controls how they interact with one another and is given in Eq. (1).

$$L_{spw} = L_0\sqrt{\frac{\varepsilon_{material}\,\varepsilon_{dielectric}}{\varepsilon_{material}+\varepsilon_{dielectric}}} \quad (1)$$

Where L_0 is the free space wave vector of the optical wave, which may be written in Eq. (2).

$$L_0 = \frac{2\pi}{\lambda_0} \quad (2)$$

λ: the typical projection beam's wavelength. The phrases indicate the dielectric properties of the medium and the metal $\varepsilon_{material}$ and $\varepsilon_{dielectric}$. The energy of the beam may be closely related to the SPW. The relationship between incident light angle and is denoted in Eq. (3).

$$L_y = L_0 m_{glass} sin\theta_{jm} \quad (3)$$

The words m_{glass} *and* θ_{jm}represent the angle of incidence and index of refractive, respectively. The following condition governs the excitation of plasmon at the metal-dielectric surface interface in a glass-metal dielectric system as signified in Eq. (4).

$$L_y = L_0 \quad (4)$$

L_y: wave vector for the surface plasmon interface. Equation (3) shows how the incident beam's wave vector is focused on the interface and aligned with the surface plasmon oscillations' propagating wave to produce resonance. When the incident light reaches the resonance threshold, there is a dip absorption in the reflectance. Additionally, the impact angle was simultaneously recorded for a range of thicknesses. Parameters, such as thickness layer (d_l), dielectric constant (ε_l) and permeability (μ_l), were analyzed. Initially, there were tangential fields $z = z_1 = 0$ and at the final limit $z = z_{N-1}$are provided by Eq. (5).

$$[W_1\ X_1\ ] = N\ [W_{M-1}\ X_{M-1}\ ] \quad (5)$$

The electric field components are represented by W_1 and W_{M-1}, the structure's layers by M_{th}, the magnetic field components by X_1 and X_{M-1}, and the feature matrix of the structure is denoted by Eq. (6)

$$N = \prod_{L=2}^{N-1} N_L \quad (6)$$

$$N_L = [cos\alpha_l\ -isin\alpha/p_l\ -isin\alpha/p_l\ cos\alpha_l\ ] \quad (7)$$

where,

$$p_l = [\varepsilon_l + m_1^2 sin^2\theta]^{\frac{1}{2}}\varepsilon_l^{-1} \quad (8)$$

and,

$$A_l = \left(\frac{2\pi e_l}{\lambda}\right)[\varepsilon_l + m_1^2 sin^2\theta]^{\frac{1}{2}} \quad (9)$$

The facial element is A_l. For p-polarized light, the amplitude reflection coefficient (s_q) is given in Eq. (10).

$$s_q = \frac{(N_{11}+N_{12}\,pM)p_1 - (N_{21}+N_{22}\,pM)p_M}{(N_{11}+N_{12}\,pM)p_1 + (N_{21}+N_{22}\,pM)p_M} \quad (10)$$

The reflection coefficient for polarized light in the M-layer model is given in Eq. (11).

$$S_p = |s_p|^2 \tag{11}$$

Therefore, when the number of layers increases, the resonance peak produces a slight shift, while the sharpness and amplitude of the dip fluctuate, and the peak size alters, becoming larger.

4. RESULT AND DISCUSSION

Investigation on the effect of gold layer thickness on SPR sensor performance is performed to determine the optimal thickness that enhances resonance angle stability, minimizes reflectance, and sharpens the resonance peak for improved sensitivity in photonic sensing applications. The gold thickness is a significant factor affecting the efficiency of SPR sensors. The resonance angle (θ_{spr}), minimum reflectance (R_{min}), and Full Width at Half Maximum (FWHM) parameters are sensitive to changes in gold thickness. By optimizing these parameters, increased sensitivity and better performance for SPR-based applications are guaranteed.

4.1 Resonance Angle and Minimum Reflectance

The behavior of sensor is observing a shift in the resonance angle with an increase in gold thickness, which is settled around 45.6° to 47.5°. Minimum reflectance becomes the least at 50 nm, corresponding to maximum plasmonic excitation efficiency. Beyond 50 nm thickness, the reflectance increases, meaning degradation in SPR sensor performance. Table 1 shows the effect of gold thickness on resonance angle and minimum reflectance. Fig. 2 shows the minimum reflectance at θ_{spr}.

Table 1 – Effect of Gold Thickness on Resonance Angle and Minimum Reflectance

L Number of Layers	Thickness of Gold (nm)	Resonance Angle (θ_{spr})	Minimum Reflectance (R_{min})(a.u)
1	20	47.54	0.50
2	30	46.3	0.26
3	40	45.8	0.10
4	50	45.6	0.01
5	60	45.7	0.08
6	70	45.6	0.28

The results show that upon growing the gold sheet's depth from 20 nm to 50 nm, the angle of resonance is reduced slightly before stabilizing at 45.2°. Minimum reflectance also has the same trend, with the minimum reflectance (0.01) found at 50 nm, which was the best SPR signal. The reflectance starts to increase after 50 nm, minimizing the SPR efficiency. The graph visually verifies that 50 nm is the ideal thickness of gold for a strong SPR response with little reflection and hence is the best suited for photonic sensor applications.

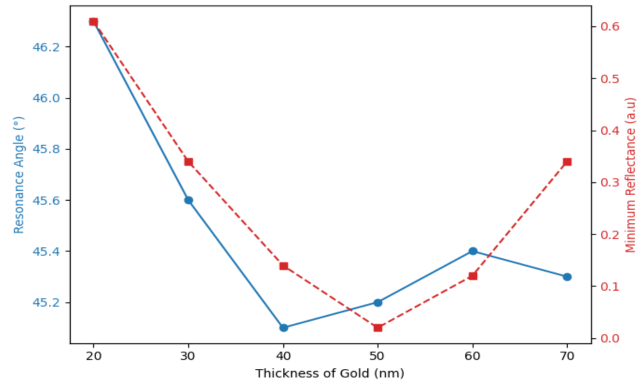

Fig. 2 – Resonance Angle and Reflectance vs. Gold Thickness

4.2 Full Width at Half Maximum (FWHM) Analysis

A lower FWHM corresponds to a sharper peak in resonance, which is preferable in high-resolution sensing devices. Table 2 shows the FWHM values for different gold thicknesses. Fig. 3 depicts the SPR curve with thickness-dependent resonance.

Table 2 – FWHM Values for Different Gold Thicknesses

L Number of Layers	Thickness of Gold (nm)	FWHM Corresponding to $\Delta\theta°$
1	20	> 4.8
2	30	> 4.5
3	40	0.42
4	50	0.50
5	60	0.65
6	701	0.55

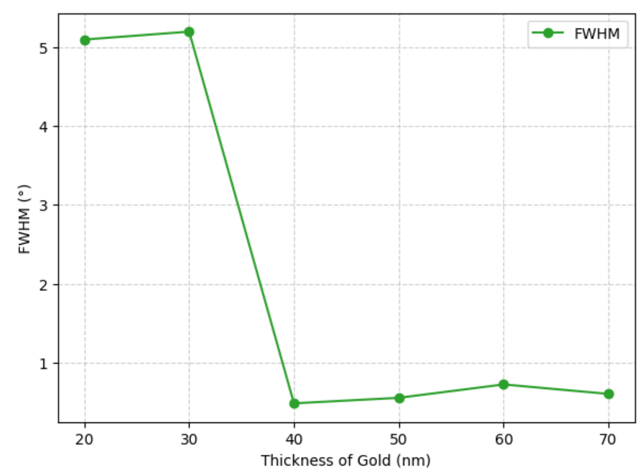

Fig. 3 – FWHM vs. Gold thickness

FWHM denotes the narrowness of the peak of the resonance. The FWHM, at 20 nm and 30 nm, is more than 5°, denoting a wider and less narrow peak of resonance and lowering the sensitivity. As the gold thickness is increased to 40 nm and 50 nm, the FWHM decreases to 0.48° and 0.55°; thus, increasing the peak sharpness as well as the sensitivity of SPR. However, beyond 50 nm, the

FWHM increases again to 0.72° at 60 nm and 0.6° at 70 nm, indicating a loss of SPR precision. Fig. 3 supports this finding; with the result that 50 nm produces the narrowest resonance peak and the best gold thickness for high-performance SPR sensing.

5. CONCLUSION

The impact of the thickness of the gold layer based on the performance of SPR and the optimal thickness for the optimal resonance angle and minimum reflectance were analyzed. An investigation of SPR response took place under controlled scenarios using thin gold films that were produced through ion-beam sputtering. The plasmonic Otto configuration measured resonance properties at a fixed wavelength point in an air-using dielectric environment. The best combination for SPR performance included a 50 nm gold layer, which delivered both minimum reflectance (0.01) and the narrowest peak width (FWHM ≈ 0.55°), according to experimental results. The reflectance characteristics along with resonance angles responded strongly to modifications in gold thickness, requiring precise thickness control for reaching optimal SPR sensitivity. The positive findings came with several unavoidable constraints. The research took place in a constant air dielectric environment yet omitted testing under variable environmental factors or alternative substrates. The research performed its analysis on gold layers only and failed to assess alternative plasmonic materials that might enhance SPR performance. Future research should examine different dielectric materials and optimize different plasmonic material compositions to determine their potential impact on improved optimization results. The integration of machine learning into SPR-based sensor creation allows to achieve higher accuracy levels by enabling the prediction of the best material thickness under various sensor conditions.

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Методика оптимізації оптичних властивостей наноматеріалів для фотонних сенсорів

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Поверхневий плазмонний резонанс (ППР) – це явище, при якому електрони на межі розділу діелектрика та металу когерентно вібрують у відповідь на вхідні плазмони. Він зазвичай використовується у фотонних сенсорах завдяки своїй чутливості до властивостей матеріалу, що робить його корисним у таких галузях, як біосенсорика та біомедичні застосування. Різні параметри, зокрема товщина металевого шару, мають значний вплив на характеристики ППР, що вимагає точних модифікацій для генерації найкращого резонансного сигналу. Існуючі дослідження не змогли заглибитися в поглиблений аналіз того, як товщина шарів золота впливає на властивості ППР у контрольованих умовах. Метою дослідження є вивчення впливу різної товщини шару золота на сигнал ППР та пошук оптимальної товщини для отримання найкращих характеристик кута резонансу та відбиття. Тонкі золоті плівки були створені за допомогою експериментального процесу, товщина якого регулювалася іонно-променевим розпиленням-осадженням. Резонанс ППР вимірювався шляхом зміни глибини шару золота та запису результуючого спектру відбиття. Зміщення кута резонансу досліджувалися з використанням плазмонної конфігурації Отто на заданій довжині хвилі в діелектричному середовищі на основі повітря. Дослідження показало, що зміни товщини шару золота призводять до значних змін кута резонансу. Результати показують, що існує оптимальний діапазон товщини для максимальної продуктивності ППР з мінімальним відбиттям та оптимальним резонансом.

Ключові слова: Поверхневий плазмонний резонанс (ППР), Шар золота, Конфігурація Отто, Фотонні сенсори, Товщина, Іонно-променеве розпилення-осадження.